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Methods to perform behind-armour debris analysis with x-ray films

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Abstract

The Behind-Armour (BA) debris cloud created behind the target after a projectile impact can easily be observed using x-ray technology. Some countries use this technology to evaluate the lethality of the threat since the number of fragments, mass and velocity can be estimated. Usually, two orthogonal x-ray stations are located behind the target in order to obtain orthogonal images at two different times. Since only projected images of BA debris are recorded on films (two dimensions), a major issue to solve concerns the available information. An analysis of these x-ray films becomes time-consuming when the fragments must be matched from one station to another or from corresponding horizontal and vertical views. Also, the distances seen on the films are projected distances that are different from the real distance travelled by fragments. This memorandum presents equations, methods and tools that can be used to rapidly locate fragments in space (three dimensions) in order to accurately compute their velocity, trajectory and finally assess their mass based on x-ray films only.

Résumé

Un nuage de débris généré derrière une cible à la suite de l'impact d'un projectile peut facilement être observé en utilisant la technologie des radiographies éclair. Quelques pays utilisent cette technologie pour évaluer la létalité d'une menace, puisque le nombre de fragments, leur masse et leur vitesse peuvent être déterminés. Habituellement, deux stations orthogonales sont situées derrière la cible afin d'obtenir des images orthogonales pour deux temps différents. Un problème majeur à résoudre concerne l'information disponible, car seule l'image projetée des fragments est enregistrée sur les films (deux dimensions). Analyser ces films de radiographie nécessite demande beaucoup de temps lorsqu'on cherche à jumeler les fragments d'une station à l'autre ou du film horizontal au film vertical correspondant. De plus, les distances sur les films sont celles projetées et non les distances réelles parcourues par les fragments. Ce mémorandum technique présente des équations, méthodes et outils qui peuvent être utilisés pour localiser rapidement les fragments dans l'espace (trois dimensions) afin de calculer avec précision leur vitesse, leur trajectoire et finalement déterminer leur masse uniquement à partir des films de radiographie éclair.

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Executive summary

A series of ballistic tests were performed at DRDC Valcartier (Defence R&D Canada – Valcartier) to study Behind-Armour (BA) debris. These BA debris were recorded on x-ray films and witness packs. X-ray films make it possible to visualise the debris cloud at a specific time. Using orthogonal stations the fragments can be observed from two different directions. The x-ray heads emit rays that are absorbed by fragments creating white areas of films. The further the fragment is from the film, the bigger the projected fragment image will be. Also, the further the fragment is toward the left or right of the emitting head, the more will the projected distance be different from the real distance. Only these projected area and distance are available at the end of the tests.

To summarise, to assess the fragment velocity or trajectory with the use of the x-ray films, one has to mathematically transform the projected distance to find the real distance travelled. This is very tricky since the fragments travel in space (3 dimensions) and the user must deal with two orthogonal projection views (2 dimensions) to define the trajectory. Therefore, up to now at DRDC Valcartier, only the projected distance on a film was used to calculate the fragments velocity. Matching fragments for one station to another and from vertical to horizontal film was performed without electronic devices, by looking only at the fragment shape and the trajectory on films. Obviously, this was time-consuming and errors could easily be made.

This memorandum present equations, methods or tools to match fragments from a film to another, to evaluate the fragment's trajectory and velocity (using the real distance travelled), and finally to estimate the fragment's mass. This can be done since the fragment's position in space will be well defined.

Since witness packs are often used in ballistic tests to record BA debris and assess fragments mass and velocity, the information obtained with x-ray can now be used to check or validate the results.

Normal impact tests using x-ray were performed at DRDC Valcartier to validate equations and models presented in this memorandum. Moreover, an Excel program was built in order to reduce the analysis time.

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Sommaire

Plusieurs essais balistiques ont été effectués à RDDC Valcartier (R&D pour la Défense Canada –Valcartier) pour étudier les débris générés derrière la cible. Ces débris ont été enregistrés sur des films de radiographie éclair et sur des panneaux témoin. Les films de radiographie permettent une visualisation du nuage de débris à un temps précis. En prenant des stations orthogonales les fragments peuvent être observés à partir de deux directions différentes. Quand les fragments passent devant les films, les têtes de radiographie émettent des rayons qui sont absorbés par ceux-ci créant ainsi une zone blanche sur le film. Plus le fragment est loin du film plus l'image projetée de celui-ci sera grosse. Par ailleurs, plus le fragment est à gauche ou à droite de la tête émettrice et loin du film, plus les distances projetées lues sur le film seront loin des distances réelles. Seules les informations sur les aires et les distances projetées sont disponibles à la fin des tests.

En résumé, pour calculer la vitesse ou la trajectoire des fragments en utilisant les films de radiographie éclair, on doit transformer mathématiquement les distances projetées pour trouver les distances réellement parcourues. Ceci est vraiment difficile à faire puisque les fragments voyagent dans l'espace (3 dimensions) et l'utilisateur doit travailler avec deux vues qui sont des projections orthogonales afin de reconstituer le trajet. Par conséquent, jusqu'à maintenant à RDDC Valcartier, le calcul de la vitesse des fragments était effectué en utilisant seulement la distance projetée sur un des films. Le jumelage des fragments d'une station à une autre et du film horizontal au film vertical était fait sans l'aide d'outils électroniques, c'est-à-dire uniquement en regardant la forme du fragment et la trajectoire parcourue sur les films. Évidemment ceci nécessitait beaucoup de temps et des erreurs pouvaient facilement se produire.

Ce mémorandum présente des équations, méthodes ou outils pour permettre le jumelage de fragments d'un film à un autre, pour évaluer la trajectoire et la vitesse de fragment (en utilisant la distance réelle parcourue) et finalement, de déterminer la masse des fragments. Ce sera possible, car la position du fragment dans l'espace sera bien définie.

Puisque les panneaux témoins sont souvent utilisés dans les essais balistiques pour enregistrer les débris générés derrière la cible et déterminer la masse et la vitesse de ceux-ci, l'information obtenue à partir des radiographies éclair peut maintenant être utilisée pour vérifier ou valider les résultats.

Des tests à angle d'impact normal ont été effectués à RDDC Valcartier à l'aide de radiographie éclair afin de valider les équations et modèles présentés dans ce mémorandum. De plus, un programme Excel a été créé pour réduire le temps d'analyse.

Y. Baillargeon and C. Lalanne. (2005). Methods to perform behind-armour debris analysis with x-ray films. DRDC Valcartier TM-2003-123. Defence R&D Canada-Valcartier.

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1.   Introduction

When a projectile impacts a target in experimental trials, a system is required to record the ballistic characteristics of this event before impact and behind the target. Three of those characteristics are the projectile velocity, integrity and yaw. X-ray technology is often used to accurately obtain all this information. Indeed, x-ray photographs taken at different times give information on the projectile flight. DRDC Valcartier's Small Caliber Laboratory has a system that is composed of two orthogonal x-ray stations and films located before and after the target. Therefore, using this system it is possible to find the real projectile velocity in a semi-automatic way knowing the distance between the x-ray stations and the time required by the projectile to go from the first station to the other. The total yaw can be obtained with the orthogonal views and the integrity check on all films.

However, some issues must be solved in order to assess individual Behind-Armour debris velocity easily. This memorandum presents mathematical equations to solve those issues. The first issue is to correctly associate fragments on horizontal and vertical films. Next, the association of each fragment from one station to the other must be made. The impact point on the witness plate also needs to be found in order to associate holes in a witness pack to the x-ray films. Once these issues have been solved and the fragment trajectory defined, the next step is to compute real fragment velocity.

Of equal concern is to estimate fragment mass with the available information. The photographs give the orthogonal fragment views at different times. Therefore, four images are available with the hole area created by the projectile on the witness plate to assess the mass. Equations are developed in this memorandum that will allow fragment characterisation (mass, velocity, trajectory).

Software have already been developed that use similar approach to analyse x-ray [1,2]. However, other techniques exist to obtain debris cloud characteristics and all present advantages and constraints. Amongst these are the holographic approach [3], switch screen approach [4] and finally an approach using a laser beam and CCD cameras [5]. The last approach uses a similar technique to the x-ray method described here. However, this memorandum will be limited to the x-ray issues to solve.

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2. Set-Up

Diagrams of the x-ray configuration found in the DRDC Valcartier Small Caliber Laboratory are presented in Figure 1, 2 and 3. The projectile comes from the left and impacts the target. This results in the ejections of multiple fragments behind the target. When these fragments are in front of the films, x-ray heads of orthogonal stations 1 and 2 are activated. Finally, fragments end their trajectory on the witness plate (WP) on the far right. The parameters indicated on Figure 1,2 and 3 are presented in Table 1. These parameters are constant.
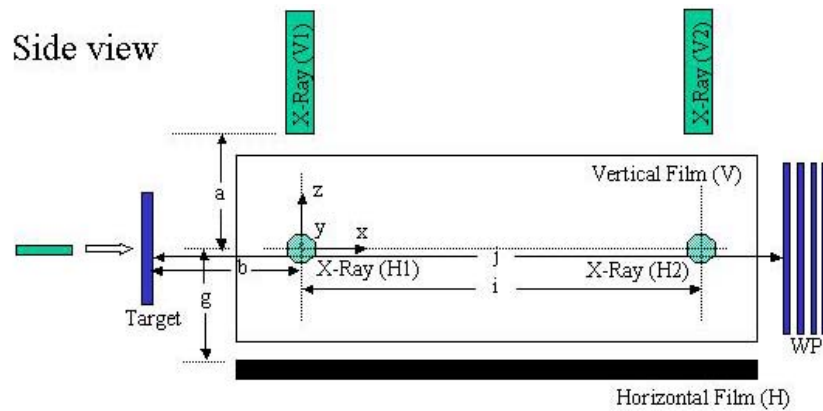

Figure 1. *Side view at normal impact*

Figure 2. *Upper view at normal impact*

Figure 3. *Side view at oblique impact angle*

Table 1. Set-up parameters

PARAMETER	SIGNIFICATION
a	Vertical distance between the x-ray station and the line of fire
g	Vertical distance between the line of fire and the horizontal film
c	Vertical distance between the line of fire and the vertical film
e	Horizontal distance between the horizontal x-ray station and the line of fire
b	Horizontal distance between the impact point on target and the reference origin (x distance)
i	Horizontal distance between the two X-ray stations
j	Horizontal distance between the impact point behind the target and the WP center
θ (theta)	Target degree of inclination

Figures 4 and 5 present the horizontal and the vertical radiography pictures of behind-armour debris. Each figure presents the double exposure of the residual penetrator and behind-armour debris at two different times. An undeformed residual penetrator and pieces of the jacket impacted the WP. In this case, the jacket is completely stripped from the core. The forward segment of the jacket is broken-up, whereas the tail segment is almost intact.
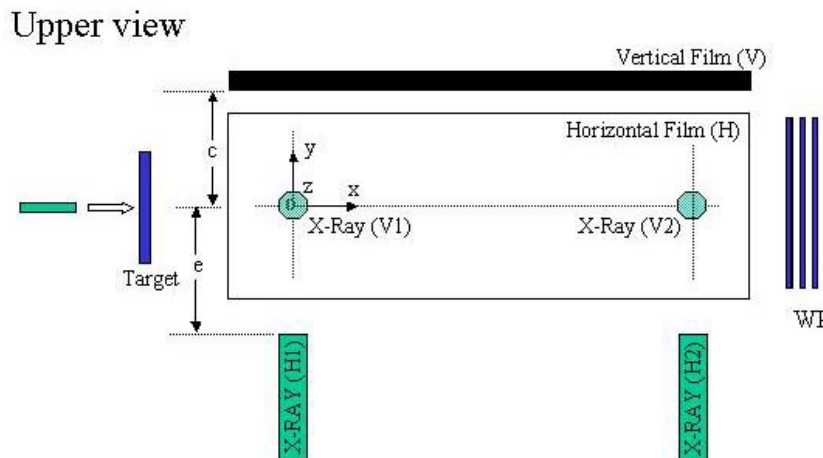
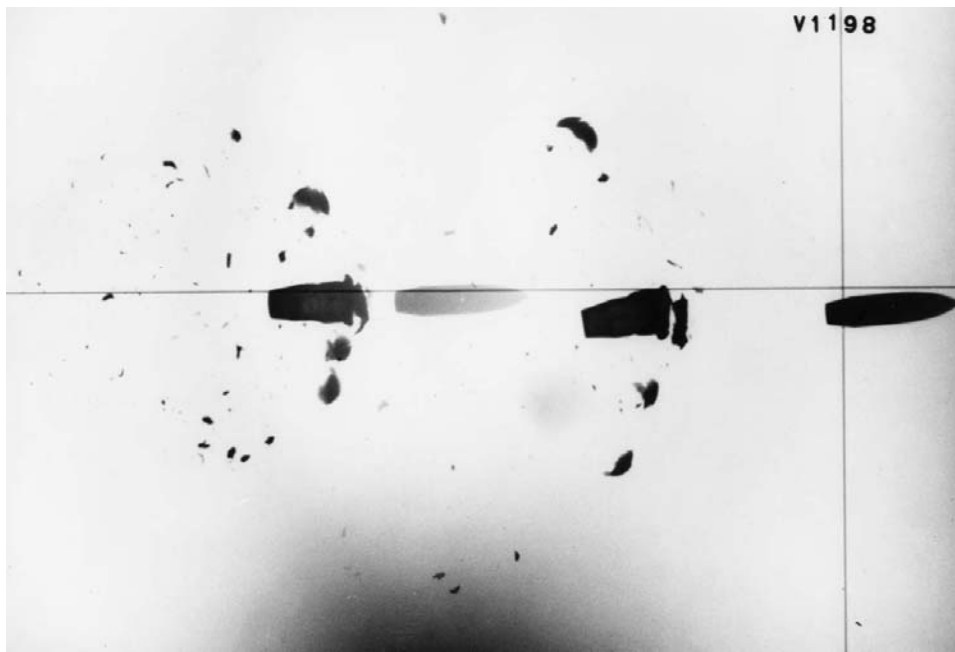*Figure 4.* Horizontal x-ray view 0.5 APM2 ammunition

Figure 5. Vertical x-ray view 0.5 APM2 ammunition

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3. Fragment projections on films

The first issue to be solved is the association of the fragment projection on films. Figure 6 presents a 3D representation of the location (P1, P2, P3) of a fragment at different times relative to the x-ray heads. Indeed, the fragment P1 is projected on two films, one placed horizontally (H) and the other vertically (V).
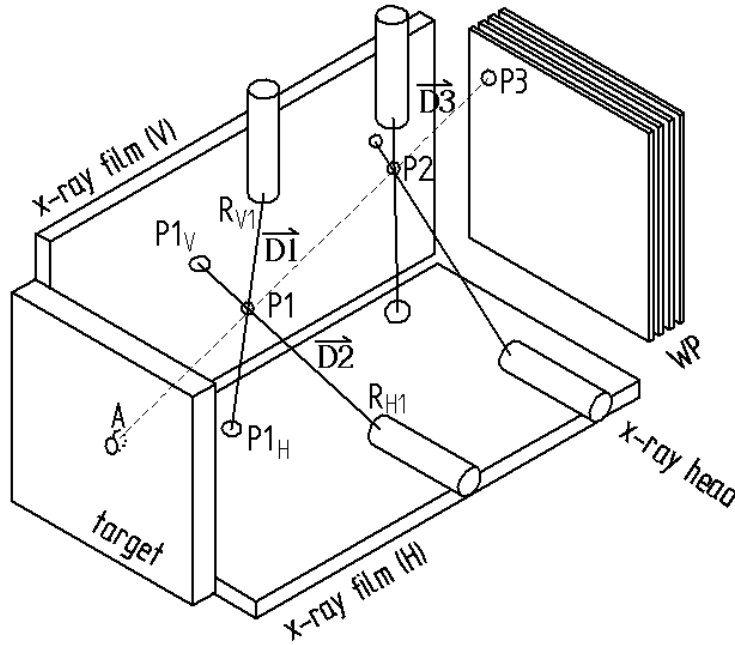

Figure 6. *Set-up (3D view)*

The characteristic that distinguishes the fragment projected images $P1_V$ and $P1_H$ from any other fragment images on the film is that their vectors ($\overrightarrow{D1}$ and $\overrightarrow{D2}$) are crossing at point P1. These two vectors are made of a line joining the fragment image on the film and the x-ray source. Equation 1 is used to evaluate the smallest distance between vectors $\overrightarrow{D1}$ and $\overrightarrow{D2}$ and will be used as a criterion to confirm that the corresponding fragment projected images are matched together.

$$D_{min} = \sqrt{(d1_x - d2_x)^2 + (d1_y - d2_y)^2 + (d1_z - d2_z)^2} \qquad (1)$$

In general, the smaller the distance, the better is the match. The fragment positions on the films were given according to the reference coordinate system (x, y, z) located at the virtual interception point of the line of fire and the normal to both horizontal and vertical X-ray heads front lens at the first orthogonal x-ray station (see Figures 1, 2 and 3). Equations 2 and 3 present the equations of vectors $\overrightarrow{D1}$ and $\overrightarrow{D2}$ that need to be solved to define the coordinates of the point on each vector that is the closest to the other vector. The coordinate of this point might not be exactly the same for both

vectors (i.e. leading to a value of D_{min} equal to 0) even if the right match has been done since there is a tolerance in measurement.

$$\overrightarrow{D1} = R_{V1} + t_m \overrightarrow{V1} = \begin{bmatrix} d1_x \\ d1_y \\ d1_z \end{bmatrix} \tag{2}$$

$$\overrightarrow{D2} = R_{H1} + s_m \overrightarrow{V2} = \begin{bmatrix} d2_x \\ d2_y \\ d2_z \end{bmatrix} \tag{3}$$

Where $\overrightarrow{D1}$ and $\overrightarrow{D2}$ give the parametric equations of a line, $\overrightarrow{V1}$ and $\overrightarrow{V2}$ are the unitary vectors and t_m and s_m are the scalar value that allow positioning on the lines. R_{V1} and R_{H1} are presented in Equation 4 and 5 and represent the x-ray stations' coordinate in space.

$$R_{V1} = \begin{bmatrix} 0 \\ 0 \\ a \end{bmatrix} \tag{4}$$

Where R_{V1} is the first vertical x-ray station position on the side view (Figure 2) and a is the distance between the x-ray station and the fire line.

$$R_{H1} = \begin{bmatrix} 0 \\ -e \\ 0 \end{bmatrix} \tag{5}$$

Where R_{H1} is the first horizontal x-ray station position on the upper view (see figure3) and e is the distance between the horizontal x-ray station and the fire line.

Equations 6 and 7 are used to compute the unity's vectors, $\overrightarrow{V1}$ and $\overrightarrow{V2}$.

$$\overrightarrow{V1} = \frac{\begin{bmatrix} x_{FH} \\ y_{FH} \\ -(g+a) \end{bmatrix}}{\sqrt{x_{FH}^2 + y_{FH}^2 + (g+a)^2}} \tag{6}$$

$$\overrightarrow{V2} = \frac{\begin{bmatrix} x_{FV} \\ (c+e) \\ z_{FV} \end{bmatrix}}{\sqrt{x_{FH}^2 + (c+e)^2 + z_{FV}^2}} \qquad (7)$$

Where $\overrightarrow{V1}$ and $\overrightarrow{V2}$ are the unitary vector required in the parametric Equations 2 and 3, respectively, x_{FH}, y_{FH} and x_{FV}, z_{FV} are parameters giving the fragment centroid position on the horizontal and vertical film, respectively, and finally, parameters g, a, c and e were defined in table 1.

In order to solve Equations 2 and 3, the two last parameters t_m and s_m must be found. The distance between $\overrightarrow{D1}$ and $\overrightarrow{D2}$ is minimum when the gradient of $\left\| \overrightarrow{D1} - \overrightarrow{D2} \right\|^2$ is equals to zero. Equations 8 and 9 present the solution in this case.

$$t_m = \frac{1}{1 - (\overrightarrow{V1} \bullet \overrightarrow{V2})^2} \left[-(R_{V1} - R_{H1})\overrightarrow{V1} + (\overrightarrow{V1} \bullet \overrightarrow{V2})(R_{V1} - R_{H1})\overrightarrow{V2} \right] \qquad (8)$$

Where t_m is a scalar value for the parametric Equation 2.

$$s_m = \frac{1}{1 - (\overrightarrow{V1} \bullet \overrightarrow{V2})^2} \left[(R_{V1} - R_{H1})\overrightarrow{V2} - (\overrightarrow{V1} \bullet \overrightarrow{V2})(R_{V1} - R_{H1})\overrightarrow{V1} \right] \qquad (9)$$

Where s_m is a scalar value for the parametric Equation 3.

Therefore, it is possible to associate the horizontal fragment projected image that best match with the vertical fragment projected image using all these equations.

Once the best match has been defined, the real fragment position in space must be estimated using Equation 10 since, as mentioned previously, equations 2 and 3 will not give the exact same coordinate. To evaluate the best real fragment position (P1), the middle of the virtual line having $[d1_x, d1_y, d1_z]$ and $[d2_x, d2_y, d2_z]$ as extremities is selected.

$$P1 = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} (d1_x + d2_x)/2 \\ (d1_y + d2_y)/2 \\ (d1_z + d2_z)/2 \end{bmatrix} \qquad (10)$$

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4. Fragment association between stations

Another issue is to associate a fragment from an x-ray station to another. As a first step, projected fragment images should have been matched by pairs for each station to define the real fragment coordinates (i.e. x, y and z). This step has been explained in the previous chapter for station 1. Once this has been done for both stations, the issue of matching fragments from station 1 to station 2 can be solved by computing the distance (D_m) between the real fragment position at station 2 (P2) and a vector $\overrightarrow{AP_1}$. Vector $\overrightarrow{AP_1}$ is defined as the line between the real fragment position in space at station 1 (P1) and the rear impact point on target (A). Vector $\overrightarrow{AP_2}$ is defined as the line between the real fragment position in space at station 2 (P2) and the rear impact point on target (A). Figure 7 presents a diagram of vectors and both x-ray stations. Equations 11, 12 and 13 give the point coordinates while Equations 14 and 15 are the vectors joining those points.
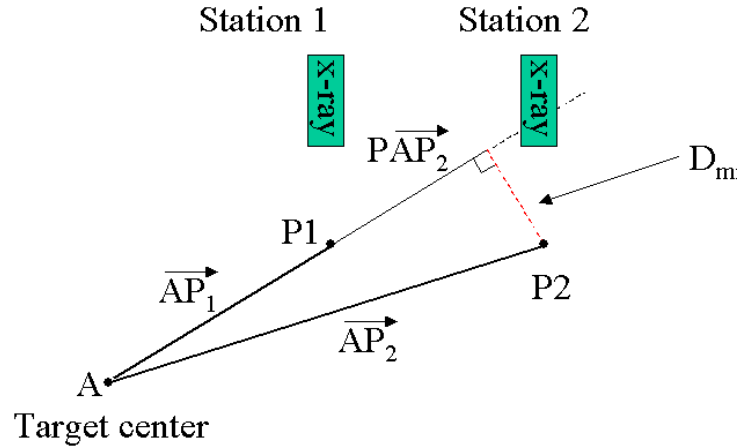

Figure 7. *Fragment position versus x-ray stations*

$$P1 = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} \qquad (11)$$

Where P1 is the fragment position at x-ray station 1.

$$P2 = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} \qquad (12)$$

Where P2 is the fragment position at x-ray station 2.

$$\vec{A} = (-b,0,0) \qquad (13)$$

Where $\vec{A}$ is the coordinate for the target center, b is the distance between impact point behind the target and the reference coordinate system (x distance).

$$\overrightarrow{AP_1} = (x_1 + b,\, y_1,\, z_1) \qquad (14)$$

Where $\overrightarrow{AP_1}$ is the line joining the target center to the fragment position at x-ray station 1.

$$\overrightarrow{AP_2} = (x_2 + b,\, y_2,\, z_2) \qquad (15)$$

Where $\overrightarrow{AP_2}$ is the line joining the target center to the fragment position at x-ray station 2.

The smallest distance (D_m) between the real fragment position (P2) and the vector $\overrightarrow{AP_1}$ is required as a criterion for matching a fragment from station one to a fragment at station 2. Obviously, the matching process involved looking at all fragments combination to obtain the smallest distance D_m (i.e. best match). The distance D_m is the length of vector $\overrightarrow{AP_2}$ minus $\overrightarrow{PAP_2}$. Equation 16 presents how to calculate $\overrightarrow{PAP_2}$ that is the projection of vector $\overrightarrow{AP_2}$ on vector $\overrightarrow{AP_1}$.

$$\overrightarrow{PAP_2} = \left(\frac{\overrightarrow{AP_2} \bullet \overrightarrow{AP_1}}{\left| \overrightarrow{AP_1} \right|} \right) \overrightarrow{AP_1} \qquad (16)$$

Equation 17 presents the distance (D_m) that will be used as a matching criterion.

$$D_m = \sqrt{(\overrightarrow{AP_{2x}} - \overrightarrow{PAP_{2x}})^2 + (\overrightarrow{AP_{2y}} - \overrightarrow{PAP_{2y}})^2 + (\overrightarrow{AP_{2z}} - \overrightarrow{PAP_{2z}})^2} \qquad (17)$$

A distance (D_m) equal to zero would mean that the two fragment coordinates (P1 and P2) are lying on a line having the origin at the middle of target (A). Once the minimal

distance is found, even if it is not equal to zero, the two fragments position (P1 and P2) are identified as best match and it is therefore possible to obtain the distance travelled by the fragment with real coordinates. This distance (D_{real}) is presented in Equation 18.

$$D_{real} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \qquad (18)$$

Where x_1, y_1, and z_1 are the real fragment coordinates at the X-ray station 1 (P1) and x_2, y_2 and z_2 are the real fragment coordinates at the X-ray station 2 (P2).

Once the real distance is calculated and the time required by the fragment to travel from one station to the other recorded, the fragment real velocity (V) can be calculated with Equation 19.

$$V = \frac{D_{real}}{t} \qquad (19)$$

Where t is the time it takes the projectile to go from one station to another.

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5. Impact point on witness plate

The objective of this section is to find where the projectile impacts on the witness plate. As seen in Figure 8, the witness plate is located according to STANAG 4190 [6].
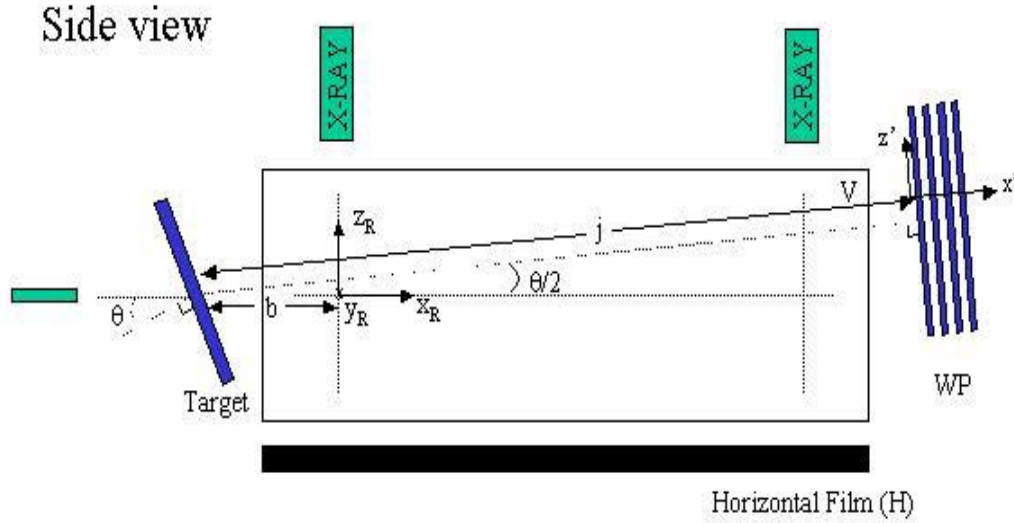

Figure 8. *Reference coordinate system (X_R, Z_R) and the witness pack coordinate system (X', Z')*

A first step is to define a line ($\overrightarrow{D3}$) passing by the target rear impact point and reaching the fragment center of impact on the witness plate (see Figure 6). Equation 20 presents this line equation according to the reference coordinate system. P1 and P2 are two points defined as fragment position at station 1 and 2, respectively, and a parameter called u_m is needed to obtain the interception on the witness plate. However, before finding the value of parameter u_m, the witness plate normal must be found with Equation 21. This is done by performing the vectorial product of the axes formed with the point randomly chosen on the witness plate (i.e. α, β, γ). These three points are taken on the witness plate as shown in Figure 9. Equations 22, 23 and 24 present the coordinate of these three points in the reference coordinate system. The constants required for these equations are defined in Table 1.

$$\overrightarrow{D3} = P1 + u_m(P2 - P1) = \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} \tag{20}$$

$$\vec{N} = \begin{bmatrix} (\beta_y - \alpha_y)(\gamma_z - \alpha_z) - (\beta_z - \alpha_z)(\gamma_y - \alpha_y) \\ -(\gamma_z - \alpha_z)(\beta_x - \alpha_x) + (\gamma_x - \alpha_x)(\beta_z - \alpha_z) \\ (\beta_x - \alpha_x)(\gamma_y - \alpha_y) - (\beta_y - \alpha_y)(\gamma_x - \alpha_x) \end{bmatrix} \qquad (21)$$
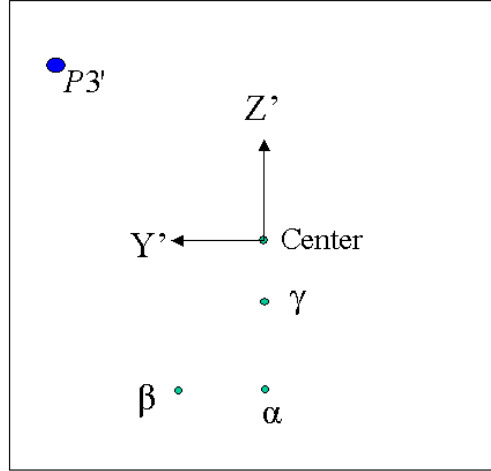

Figure 9. *Witness plate reference axes*

$$\alpha = \left(\frac{j}{\cos\dfrac{\theta}{2}} - b, 0, 0 \right) \qquad (22)$$

$$\beta = \left(\frac{j}{\cos\dfrac{\theta}{2}} - b, 1, 0 \right) \qquad (23)$$

$$\gamma = \left(\frac{j}{\cos\dfrac{\theta}{2}} - b - \tan\frac{\theta}{2}, 0, 1 \right) \qquad (24)$$

Once the normal has been defined, Equation 25 can be solved to find the value of ''u_m'' since the scalar product of perpendicular vectors is equal to zero. Equation 26 presents the solution for ''u_m'' , which can now be used in Equation 20 to find P3.

$$(\overrightarrow{D3} - \alpha) \bullet \overrightarrow{N} = 0 \tag{25}$$

$$u_m = \frac{(\alpha_x - x_1)N_x + (\alpha_y - y_1)N_y + (\alpha_z - z_1)N_z}{(x_2 - x_1)N_x + (y_2 - y_1)N_y + (z_2 - z_1)N_z} \tag{26}$$

Where u_m is the parameter for finding a point on the witness plate, x_1, y_1, z_1 are the real fragment coordinates for the x-ray station 1 (P1), x_2, y_2, z_2 are the real fragment coordinates for the x-ray station 2 (P2) and N_x, N_y, N_z are the coordinate for the vector orthogonal to the witness plate.

Since the fragment position P3 on the witness plate is given according to the reference coordinate system (X_R, Y_R, Z_R), a change is required to give the fragment position according to a coordinate system located on the witness plate (x', y', z'). Figure 8 presents these new reference axes with the witness plate center as the origin and Equation 27 presents the fragment position on the witness plate according to this new reference.

$$P3' = \begin{bmatrix} x_3 \cos\frac{\theta}{2} - j\left(\cos\frac{\theta}{2}\right)^2 + b\cos\frac{\theta}{2} + j\left(\sin\frac{\theta}{2}\right)^2 - z_3 \sin\frac{\theta}{2} \\ y_3 \\ x_3 \sin\frac{\theta}{2} - j\sin\frac{\theta}{2}\cos\frac{\theta}{2} + b\sin\frac{\theta}{2} + z_3 \cos\frac{\theta}{2} - j\cos\frac{\theta}{2}\sin\frac{\theta}{2} \end{bmatrix} = \begin{bmatrix} x_3' \\ y_3' \\ z_3' \end{bmatrix} \tag{27}$$

Where P3' is the fragment position on the witness plate from the center of the plate, x_3, y_3, z_3 give the fragment position according to the reference coordinate system, ' j ' is the distance between the witness pack center and the impact point behind the target, ' b ' is the distance between the impact point behind the target and the reference coordinate system and finally 'θ' is the target degree of inclination.

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6.   Estimate of the mass

The objective of this section is to find a way to estimate fragment mass based on the projected fragment area and the hole area caused by the fragment on the witness plate. Indeed, there are two horizontal and two verticals views representing the fragment-projected area. Therefore, a technique for measuring the projected area based on icosahedron's method is used according to STANAG 4589 [7]. Also according to STANAG, the projected area is the area of a tumbling fragment in flight at a given time and rotation. An icosahedron is a 20-sided figure, which has 10 different faces. The projected area will then be a mean value of those corrected areas. Since, only 4 different faces are available on the film for this present study, the mean is taken on those 4 corrected areas as computed in Equation 28. The fragment area found on the films will not be used directly since a fragment image is projected on the film, which is not the real fragment area. A correction is therefore required to obtain the real projected fragment area. Equation 29 presents a way to assess this correction for a fragment seen at the first station on the horizontal film (Figure 1). A shape factor is also required to estimate fragment mass. This factor is presented in Equation 30.

$$A_c = \frac{A_{c1H} + A_{c1V} + A_{c2H} + A_{c2V}}{4} \qquad (28)$$

Where A_c is the average corrected projected fragment areas and A_{c1H}, A_{c1V}, A_{c2H}, and A_{c2V} are the corrected projected fragment area of the 4 views on the film.

$$A_{c1H} = A1_H \left(\frac{a - z_1}{g + a} \right)^2 \qquad (29)$$

Where $A1_H$ is the fragment-projected area as seen on the horizontal film at the first x-ray station, z_1 is one of the coordinates of the fragment (P1) and the other parameters are defined in Table 1.

$$m = \left(\frac{A_c}{f_k} \right)^{3/2} \qquad (30)$$

Where m is the estimate fragment mass and f_k the shape factor.

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7.   Procedure

The objective of this section is to resume the procedure in order to obtain the real fragment velocity and its estimated mass. This is done in step 1 to 5.

1. Select a fragment on a view on the first station and then match this fragment with all fragments on the other view and, for each pair of fragments, compute the minimum distance between the two vectors using Equation 1. The best result should indicate a perfect match. If more than one fragment give a very good result, two additional criteria could be considered. First, the length of the fragment in the ''x'' direction on each view should be similar. Moreover; the distance from the reference coordinate system to the fragment centroid should also be very similar. These last two criteria could save computing time and avoid bad matching.

2. Repeat step 1 for station 2.

3. The objective of step 3 is to associate fragment from a x-ray station to the other by computing the distance between the fragment at station 2 and the line which joins the fragment at station 1 and the rear impact point on target (Equation 17). The smallest distance should indicate the best match.

4. Once all fragments are matched, the results can be validated using the supposed impact point on the WP (Equation 27). However, if there is no fragment hole located on the WP at a supposed impact point, then the match was not right or the fragment did not have enough energy to create a hole. Finally, a graphic of the fragment velocity calculated versus fragment position in space could help to confirm the matching accuracy [1].

5. Once these steps are completed, Equation 18 allows computing the real distance travelled by the fragment between two x-ray stations and Equation 19 allows computing the fragment velocity. The last step is to estimate fragment mass from 4 fragment views on x-ray films. This is done by first computing the mean corrected fragment projected area with Equation 28 and then applying Equation 30 to estimate fragment mass. The fragment area on WP could also be used has additional information to find the average area. However, one should consider that the area seen on a witness pack is bigger than the real fragment area [8].

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8.   Conclusion

This memorandum presented a way of calculating a fragment velocity, trajectory and estimating its mass from x-ray photographs taken in a physical installation, including a target and a witness pack. In order to easily collect information, mathematical equations had to be developed. Using these equations the association of fragment from the horizontal film to the vertical film and from station one to station two is now feasible. Also, the results obtained with witness packs can now be compared with those obtained from x-ray systems.

The major objective of this memorandum was to develop a method for computing the real fragment velocity. An equation was developed to allow this computation. Of equal concern was to estimate fragment mass with the information available. The photographs showed the fragment projections at different times. Therefore, two overheads and two side views were used to find an equation for the fragment mass estimation. However, there are some limitations to the method presented in this memorandum. Indeed, since the references are taken according to the centroid, the method is more accurate for small projectiles. Also, smaller is the projectile better is estimated the fragment ejection point. The number of fragments must be restricted to associate them accurately on the x-ray films. And finally, it is assumed that fragments travelled along a straight line.

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9.   Future work

Metallic spheres have been suspended in the impact chamber at different positions to validate the fragment matching criteria for horizontal and vertical films. Also, some films obtained from experimental tests have been analysed to prove the concept and again validate the process. Future work should involve an experimental test where the fragment velocity calculated with x-ray would be compared with the velocity obtained using an independent system (e.g. a camera to record the flash on a metallic witness sheet). Finally, fragments could also be recovered to measure the real mass.

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10. References

1. T.N. Ramsay and R.E. Eureka, "Locating digitized Behind Armour Fragments", 47th Aeroballistic Range Association Meeting French-German Research Institute of Saint-Louis, France, October 13-18, 1996.

2. G.J. Oosterom and G.M.J. Van Soest, "Software Description Document – Processing of Spatial Fragment Distribution Images", T728/PDD2/V10, 1995.

3. BJ. Thompson, "Holographic optics II: Principles and Applications", SPIE vol. 1136, Pages 308-326, Paris, France, 25-28 April 1989.

4. R. Barnard and P. Nebolsine, "Fragment-Field Analysis Testing System", Physical Sciences Inc Andover MA, AD-A405 521, Jan. 2000.

5. C. Anderson, "Development of an Electric, Behind the Armor Debris Witness Panel", Air Force Office of Scientific Research, AFRL-SR-BL-TR-01-0559, Jan. 2001.

6. STANAG 4190, "Test Procedures for Armour Perforation Tests of Anti-Armour Ammunition", Edition 2, Military Agency for standardisation, 1996.

7. NATO, "Ratification of STANAG 4589 (Edition 1) on Static Testing of High Explosive Munitions for Obtaining Fragment Spatial Distribution", North Atlantic Council, 2000.

8. Y. Baillargeon and C. Lalanne, "Hole Growth Equation Related to Al-1100 Witness Plates", DRDC Valcartier TM 2003-122, August 2004, UNCLASSIFIED.

List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
BA	Behind-Armour
a	Vertical distance between x-ray station and fire line
g	Vertical distance between fire line and horizontal film
c	Horizontal distance between fire line and vertical film
e	Horizontal distance between horizontal x-ray station and fire line
b	Horizontal distance between impact point behind target and indicator (x distance)
i	Horizontal distance between two stations
j	Horizontal distance between impact point behind target and WP center
θ	Target degree of inclination
D_{min}	Minimum distance between two vectors $\overrightarrow{D1}$ and $\overrightarrow{D2}$
D_m	Minimum distance between a point P2 and the vector $\overrightarrow{AP_1}$
D_{real}	Real distance travelled by the fragment between two x-ray stations
A_c	Average corrected projected fragment area
m	Estimated fragment mass
f_k	Shape factor
WP	Witness pack
$\overrightarrow{D1}$	Parametric equation of a line with extremities at R_{V1} and $P1_{H.}$
$\overrightarrow{D2}$	Parametric equation of a line with extremities at R_{H1} and $P1_{V.}$

$\overrightarrow{D3}$	Parametric equation of a line going through P1 and P2
R_{V1}	Position of the first X-ray station for the vertical view
R_{H1}	Position of the first X-ray station for the horizontal view
P1$_H$	Position of the projected fragment image on the horizontal film at station 1
P1$_V$	Position of the projected fragment image on the vertical film at station 1
t_m	Scalar value to define a specific position on a line
s_m	Scalar value to define a specific position on a line
$\overrightarrow{V1}, \overrightarrow{V2}$	Unitary vectors
A	Target center
$P1$	Real fragment coordinate at x-ray station 1 in the reference coordinate system
$P2$	Real fragment coordinate at x-ray station 2 in the reference coordinate system
$P3$	Real fragment coordinate on the WP in the reference coordinate system
$\overrightarrow{AP_1}$	Vector joining the target center and fragment position (station 1)
$\overrightarrow{AP_2}$	Vector joining the target center and fragment position (station 2)
$P\overrightarrow{AP_2}$	AP_2 vector projected on AP1 vector
V	Fragment velocity
t	Time taken by the fragment to travel from station 1 to station 2
$x_{FH},$	Fragment centroid position on the horizontal film according to x axe

y_{FH},	Fragment centroid position on the horizontal film according to y axe
x_{FV},	Fragment centroid position on the vertical film according to x axe
y_{FV},	Fragment centroid position on the vertical film according to y axe
α, β, γ	Points on the witness plate
$\overrightarrow{N}$	Orthogonal vector to the witness plate
u_m	Scalar value to find a point ($\overrightarrow{P_3}$) on the witness plate lying on the line $\overrightarrow{D_3}$
P3'	Fragment position on the witness plate (coordinate system located at the center of the WP)

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(U) The Behind-Armour (BA) debris cloud created behind the target after a projectile impact can easily be observed using x-ray technology. Some countries use this technology to evaluate the lethality of the threat since the number of fragments, mass and velocity can be estimated. Usually, two orthogonal x-ray stations are located behind the target in order to obtain orthogonal images at two different times. Since only projected images of BA debris are recorded on films (two dimensions), a major issue to solve concerns the available information. An analysis of these x-ray films becomes time-consuming when the fragments must be matched from one station to another or from corresponding horizontal and vertical views. Also, the distances seen on the films are projected distances that are different from the real distance travelled by fragments. This memorandum presents equations, methods and tools that can be used to rapidly locate fragments in space (three dimensions) in order to accurately compute their velocity, trajectory and finally assess their mass based on x-ray films only.

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X-ray, fragment, witness pack, witness plate, fragment mass, fragment velocity, behind-armor debris, behind-armour debris, x-ray film, fragment trajectory, orthogonal view, orthogonal image, orthogonal film.

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